Deep Space Station 13: Deep Space Network Research and Development 34-m Beam Waveguide Antenna

Introduction

For many years, NASA's Deep Space Network (DSN) has relied on a research and development (R&D) antenna station for technology development, for demonstration and to prepare for the infusion of new capabilities into the operational DSN. Deep Space Station 13 (DSS 13) is both a logical concept and a physical realization appropriate to the needs of the DSN. The current manifestation of DSS 13 is a 34-m Beam Waveguide (BWG) antenna. Initiated as a project in 1987, DSS 13 was designed and constructed during 1988 and 1989, seeing first light in 1990. It was the first BWG antenna constructed in the DSN and has operated continuously for nearly a decade [Smith 1986, Britcliffe et al. 1991].

There were a number of motivations for upgrading DSS 13 from a 26-m Cassegrain telescope to a 34-m BWG antenna. The DSN required a stiffer antenna with a better surface to serve as a test bed for Ka-band. In addition, the DSN was interested in exploring the BWG concept both as an approach for the implementation of new apertures and as an option for retrofitting existing antennas to improve performance. Because the radio frequency (RF) beam is "guided" by microwave mirrors and reflectors, from the Cassegrain focus to a focal point below the elevation axis, all sensitive electronics can be housed in an easily accessed, non-tipping space protected from the weather. Since this instrumentation area is much larger than the cone of a typical Cassegrain antenna, additional equipment can be readily staged as well. This results in better performance at X- and Ka-bands and lower-cost maintenance and operations [Clauss and Smith, 1986].

DSS 13's initial role was to serve as a comprehensive test bed for all development and implementation issues relevant to improving DSN capability by employing BWG technology and as the site for the push up in frequency to Ka-band. Its canonical role since has been:

- To provide a general test and demonstration environment for new microwave and system instrumentation concepts
- For automation and remote operations applicable to deep space communications
- To support scientific technology development and observation.

With the construction of the first of the operational BWG antennas—DSS 24, DSS 25 and DSS 26—the technology development emphasis shifted from the antenna itself to microwave instrumentation, performance improvement, and end-to-end ground system demonstration. The DSN has committed to the implementation of Ka-band, particularly in support of the radio science objectives of the Cassini mission. Optical communications has emerged as a potential, far future, high-data-capacity telemetry channel. The station's current goal is to serve as the site for technology development leading to the *future radio frequency* DSN. DSS 13 is achieving this goal by:

- Operating as a frequency-agile instrument capable of world-class, ground-based radio astronomy, interferometry and radio science.

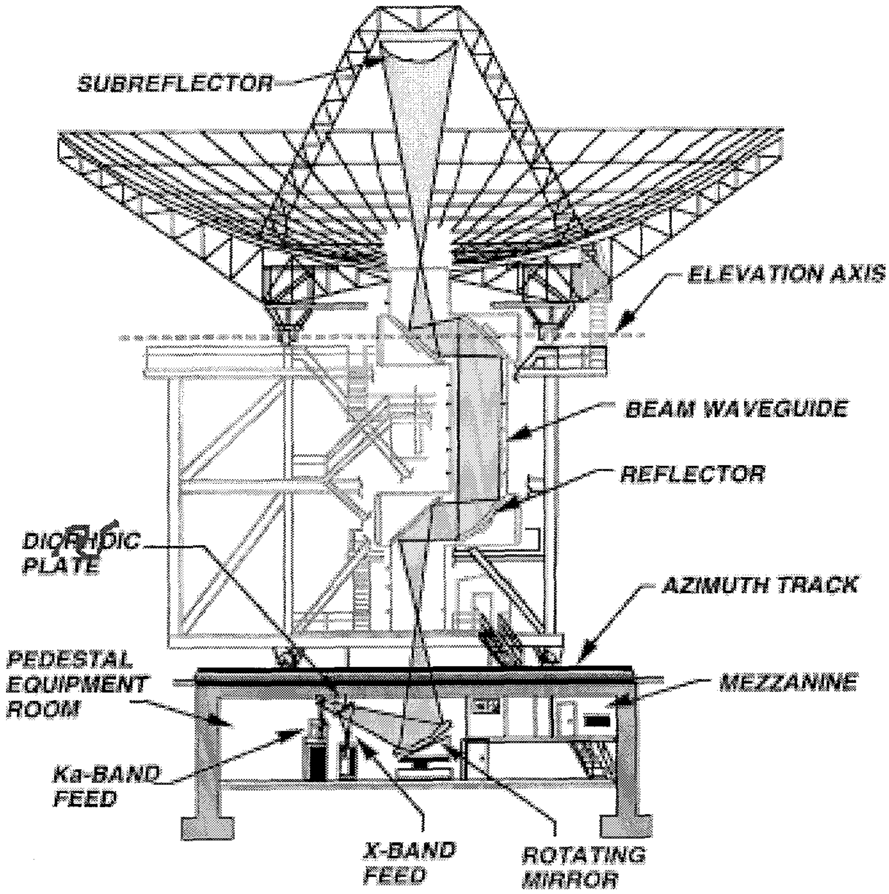
- Implementing and refining a high frequency (> X-band [8 gigahertz (GHz)]) observational capability, including gravity compensation for surface deformation.
- Maintaining an ultra-low-noise capability, utilizing maser amplifier-based receivers.
- Renewing its emphasis on automation, in particular, on increasingly autonomous ground station operations.

This vision has guided DSS 13 development and utilization for the last three years while, simultaneously, the station continues to play its canonical test and demonstration role.

Capabilities

Similar to the operational BWGs, DSS 13 has a 34-m shaped-surface main reflector, with a center-fed beam waveguide. Its shaped-surface subreflector is supported by a tripod superseded by a more rigid, quadripod support on the operational antennas. Four intermediate mirrors reflect and focus the beam and deliver the RF signal to a large, subterranean, pedestal room located beneath the antenna mechanical structure. The pedestal room is stationary, unlike the main reflector, which must tip in elevation and rotate in azimuth to follow sources as they move across the sky.

As an R&D telescope, unlike the operational BWGs, DSS 13 has evolved from an open pedestal design, with a focal ring that now accommodates six, instrumented feed horn and receiver packages positioned on the pedestal floor. Sharing the same primary optics, RF energy can be directed at each of the feed positions in the focal ring by rotating a computer-controlled, ellipsoidal mirror. Final focus onto individual receivers is accomplished by flat mirrors, sometimes in conjunction with transmissive/reflective dichroic plates for simultaneous, dual-frequency operation. The DSS 13 antenna structure and complete optical path are illustrated in Figure 1.



DSS 13's servo, encoder and antenna control subsystems were upgraded in 1998 to the emerging DSN standard antenna-pointing controller, the APC. The APC has been implemented on the operational BWGs and will be delivered on the high efficiency (HEF) and 70-m antennas by 2003. One of the challenges facing DSS 13 is maintaining sufficient compatibility with the rest of the DSN so that new DSN systems can be readily staged at the facility for subsystem, integration and end-to-end testing. Embracing new technology in fundamental systems which is subsequently not adopted by the DSN can also leave DSS 13 out of step with the operational network, impairing the station's ability to play its test and integration role.

DSS 13's richest asset, and what distinguishes it most from its operational counterparts, is its extensive set of front-end feed horns and receivers. Presently, there are *ten* operable receivers in residence at the station:

1. S-/X-band (2/8 GHz) dual-frequency Very Long Baseline Interferometry (VLBI) receiver – standard DSN VLBI dual-frequency package in a single refrigerator. Selectable right or left circular polarization (RCP or LCP).

2. DSN X-band (8 GHz) receiver – standard DSN single polarization (RCP).

3. X-band (8 GHz) ULNA radar receiver – liquid helium-cooled maser, simultaneous dual polarization (RCP/LCP).

4. Ku-band (13.8 GHz) Cassini-JMOC receiver – developed in collaboration with the Goldstone-Apple Valley Radio Telescope project (GAVRT), a science education outreach activity, for the Cassini-Jupiter Microwave Observing Campaign (JMOC). Matched in frequency to the Cassini radar instrument.

5. K-band (22 GHz) Dicke beam-switch receiver – dual horn, three channel package, operable either in simultaneous dual polarization (RCP/LCP) mode or in single polarization, beam-switch mode.

6. Ka-band (32 GHz) monopulse receiver – single polarization (RCP) with integrated monopulse tracking coupler for closed-loop, precision spacecraft pointing.

7. Ka-band (32 GHz) broadband low-noise receiver – R&D modification of the DSN's first Ka-band receiver.

8. Ka-band (34 GHz) Zeeman maser receiver - liquid helium-cooled maser, simultaneous dual polarization (RCP/LCP) [Levin and Hofhine 2000, Levin et al. 2001].

9. Q-band (43 GHz) R&D receiver – cryogenically cooled high-electron-mobility (field-effect) transistor (HEMT), simultaneous dual polarization (RCP/LCP).

10. W-band (90 GHz) R&D receiver – currently under development as a collaboration between InterPlanetary Network and Information Systems Directorate (IPN-ISD) Technology program and DSN radio astronomy.

Detailed front-end specifications for all the receivers resident at DSS 13 can be found on the station's web page at http://Ntserve.gdscc.nasa.gov/13site.html.

DSS 13 maintains a modest transmit capability for uplink, a 20 kilowatt (kW) transmitter at X-band and an 80 watt (W) transmitter at Ka-band (34 GHz). Although limited in power, until quite recently DSS 13 possessed the only Ka-band uplink available in the DSN.

Intermediate frequency (IF) signals are routed from the pedestal via a 16 x 4 channel IF matrix switch. The selected IF channels are transmitted over optical fibers to the control room where they can be distributed to a number of back-end processors:

- Precision, two-channel radiometer
- Full-spectrum recorder (FSR)
- Radar downconverter
- Wide-Band Spectrum Analyzer (WBSA)
- VLBI MkIV Data Acquisition Terminal (MkIV DAT)—The station's VLBI capability is complemented by the Real-Time Block II correlator (RTB2), a device that can take

formatted data streams from two MkIV DATs and extract interferometric fringes in real time, thus constituting a connected-element interferometer (CEI).

Six optical fibers connect DSS 13 to Goldstone's main signal processing center (SPC 10).

- Two fibers carry precision frequency and time information to DSS 13 from SPC 10
- Two normally deliver radar data from the DSS 13 radar downconverter to SPC 10 radar processors
- One delivers IF data from DSS 14, the 70 m antenna, to DSS 13's microwave spectrometers
- One is dedicated to bringing formatted VLBI data from SPC 10 to the RTB2.

Note that there is no reference to a *telemetry* capability. DSS 13's telemetry capability has not been upgraded since the prototypes of the Block V Receiver (BVR) were tested at the station. Because of the initial hardware cost hurdle, attempts to renew DSS 13's downlink telemetry capability have failed.

The monitor and control environment (M&C) at DSS 13 has been transformed over the past two years to support the transition to the APC, to provide a foundation for automation and remote observing, and to bring the station into conformity with the Research & Development Control System (RDC). The RDC is an R&D community-uniform architecture for data acquisition, antenna command and control, and automation used by DSN Science, VLBI and R&D elements of the DSN at all three operational complexes. The RDC is comprised of the Equipment Activity Controller (EAC), the Radio Astronomy Controller (RAC), the PC Field System (PCFS), and interfaces for M&C and messaging. The EAC serves as the station master controller, as a gateway to DSN-standard subsystem controllers, and as an automation engine. The RAC controls *instruments* such as ambient loads, noise diodes, power meters and synthesizers. The PCFS is the MkIV DAT and VLBI execution controller. A challenge facing the M&C at DSS 13 is that the station depends on the RDC for its automation effort and for science observing while simultaneously striving for compatibility with the future M&C environment currently planned for the DSN, the Network Monitor & Control (NMC).

Recent Accomplishments

DSS 13 has been instrumental in the development of nearly all the ground station technologies required by the Radio Science experiments to be conducted by the Cassini mission, as well as validating the performance of the on-board instrumentation dedicated to Radio Science:

- The monopulse tracking coupler, a closed loop, feedback-driven system for precise antenna pointing, was demonstrated at DSS 13. It has since been transferred to operations as an embedded element of the monolithic X/X/Ka receiver.
- The beam aberration and point ahead system was required to offset the transmit and receive beams. This was to compensate for tangential spacecraft motion during the long, round-trip light times to Cassini. The system was first demonstrated at DSS 13 and has been transferred to operations.

- The Cassini media calibration system, in particular, the Advanced Water Vapor Radiometer (AWVR) which is critical to the Gravity Wave Experiment, was validated by the CEI-AWVR comparison experiment carried out with simultaneous observations from DSS 13 and DSS 15. The exceptionally radiometrically-stable receiver from the AWVR was used to explore the BWG-embedded AWVR concept. This activity pioneered the use of a potential seventh "suspended" feed position by hanging the receiver from the pedestal room ceiling and looking directly at the ellipsoid.
- A critical, in-orbit instrument checkout that used DSS 13's Ka-band uplink:
  - confirmed the functionality of the Cassini Ka-band translator
  - demonstrated the first Ka-band downlink coherent with a Ka-band uplink
  - demonstrated the first, three-link configuration (simultaneous X-band/Ka-band downlink coherent with X-band uplink).

The prime observing phase of Cassini-JMOC recently concluded. Using a receiver developed specifically for this work and matched in frequency to the 13.8 GHz Cassini Radar instrument, JMOC measured Jupiter's microwave emission from the ground while similar measurements were made from the spacecraft. The observations were conducted remotely by students throughout the nation under the auspices of the Goldstone-Apple Valley Radio Telescope (GAVRT) project. The GAVRT project is a science outreach collaboration between JPL and the Lewis Center for Educational Research. The strong synergy between GAVRT's remote operation model and DSS 13's automation objectives significantly accelerated the station's transition to the remote, unattended observing mode. JMOC's need for a precise, absolute calibration required the application of the raster continuous scan technique and rejuvenated work on advanced antenna calibration methods.

Employing its FSR, DSS 13 supported the detection of Beacon Monitor tones from both the MGS and DS1 spacecraft. This work migrated from DSS 26 to DSS 13 for programmatic reasons. The need to support the Beacon Monitor Operations concept (BMOX) helped shape the DSS 13 vision for increasingly autonomous operations.

DSS 13 was also regularly used for the development of the lunar neutrino detection technique. A JPL-UCLA collaboration, this exploratory program seeks to detect short electromagnetic pulses originating from particle interactions in the surface of the moon, thereby establishing a new approach to neutrino astronomy [Gorham et al. 2000].

Current Advanced Technology Activities

DSS 13 currently participates in a number of advanced technology activities supported by the IPN-ISD Technology program.

The DSS 13 W-band Assessment is exploring the viability of the DSN BWG subnet at frequencies from 80-90 GHz. The motivations for this effort are:

- Technology development and demonstration for future space VLBI missions such as ARISE, as well as millimeter-wave VLBI in general.
- Ground-based radio astronomical observations, world-class science aligned with NASA's Origins and Structure and Evolution of the Universe themes.

- Gravity compensation measurements at Ka- and W-band in support of Ka-band implementation on the 70-m antennas
- Future DSN telecommunications at a high-data capacity, atmospheric transmission window between Ka-band and optical

DSS 13 provides an ideal facility for gravity compensation work, required by the DSN to utilize its 70-m antennas at Ka-band. The deformable flat plate has been installed at the station and will be used in August in conjunction with the Array Feed Compensation System (AFCS) for an extensive Ka-band test with Cassini. Moreover, since the *scale* of the gravity compensation problem goes like D/λ, the diameter of an antenna measured in wavelengths, W-band provides a context for the investigation of the gravity compensation problem at a similar scale.

DSS 13 Autonomous Operations strives to develop a generic remote observing capability, to increase station utilization without increasing operational cost, to provide a rapid prototype, alternative approach which complements the DSN's automation effort, and to meet the automation needs of the station's science customers. This work is proceeding along a trajectory of increasing autonomy, from robust/remote operations through remote/unattended operations to autonomous/unattended operations. Robust/remote has been achieved. Remote/unattended—unattended at the station but supervised by a remote, human intelligence—has been demonstrated by trusted users, that include the development team and GAVRT operators. The transition to remote/unattended as a general capability is occurring right now. It will be made available broadly to all interested users once they have been trained and certified by DSS 13 personnel.

Our goal is to achieve remote/unattended—unattended at the station and supervised solely by machine intelligence—by the end of fiscal year 2002. The culmination of DSS 13 autonomous operations, if achieved, would be the realization of the *self-awakening station* concept.Initially in a quiescent state, a self-awakening station would:

1. Detect unutilized capacity
2. Map a user to the opportunity
3. Plan an activity
4. Configure its hardware
5. Conduct the observation
6. Inform and deliver data to the selected user
7. Return to its quiescent state.

Utilization

DSS 13 has traditionally been sponsored by the Technology, Engineering, and Plans and Commitments (DSN Science) offices of the InterPlanetary Network and Information Systems Directorate (IPN-ISD, formerly TMOD). A study was conducted this year to assess overall station utilization and to estimate station usage by each of its major sponsoring organizations. The study showed the station to be heavily utilized. In calendar year 2000, although only nominally operated five prime day shifts per week, DSS 13 supported 256 passes totaling 1894 observing hours. This averages to ≈ 236 8-hour (1894/8) passes or 4_ 8-hour (236/8) passes per week. (This does not take into account downtime for maintenance, infrastructure development or major station reconfiguration.) The station is typically scheduled for one 8-hour maintenance pass per week, although maintenance is often done on a non-interference basis in order to support more observation.

The assignment of users and projects to DSN Science, IPN-ISD Technology, and IPN-ISD Engineering was sometimes arbitrary. Observations conducted specifically in support of tasks funded by IPN-ISD Technology or called out in DSN Science Project Service Level Agreements (PSLAs) are unambiguous. However, new technology demonstrations that establish proof-of-principle prior to operational implementation but are regarded as advanced engineering rather than advanced technology are labeled as IPN-ISD Engineering. For example, the Cassini Radio Science in-orbit checkout, beam aberration, and point-ahead observations were assigned to this category.

The utilization study revealed a more balanced usage than anticipated:

• DSN Science	125 passes / 1010 hours	49 % / 53 %
• Technology	68 passes / 428 hours	26 % / 23 %
• Engineering	63 passes / 456 hours	25 % / 24 %

Future Directions and Challenges

DSS 13 will continue to be guided by the vision that has defined its evolution for the last three years. This is based on frequency agility, the development of high frequency capability, and an increasingly autonomous station concept. We hope to significantly expand the scope of the W-band activity. Preliminary results from the W-band assessment indicate that a serious effort must be made to achieve the aperture efficiency required to be an effective instrument at millimeter wavelengths. Options include improving the surface figures of the main reflector, subreflector, and intermediate mirrors and applying compensation techniques such as the DFP or, perhaps, a deformable subreflector. We hope to apply the new closed-loop pointing technologies that are currently being developed for precise Ka-band blind pointing. We also hope to be active in advanced antenna calibration; DSS 13 is the natural site for the development of the methodologies and instrumentation needed for high-data rate, continuous scan calibration techniques.

The station also must face a number of challenges. Can it continue to serve its canonical role without renewing its downlink telemetry capability? DSS 13 should possess prototypes of the DSN's emerging telemetry engines: the Downlink Telemetry and Tracking subsystem (DTT) and the Radio Science Receiver (RSR), an upgraded version of the FSR capable of two-channel tone extraction and telemetry arraying. Should the station diversify its user base by supporting occasional operational users, risking its relaxed flavor of configuration control and freedom from the rigorous demands of flight project customers? If DSS 13 can meet these challenges the station will continue to be a rich, important, and unique asset of the DSN well into the next decade.

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